Efficient multi-stage vacuum pump sets for steel degassing

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In secondary metallurgy, vacuum pumps are used in steel refining units such as VD, VOD and RH. For many years, steam ejector pumps have been used in these applications. However, the equipment of the future are mechanical vacuum pump systems, particularly energy-efficient pump sets of four or five stages.
Modular four- or five-stage pump systems combine high functionality and low energy consumption.
This article deals with aspects useful to set up an optimal vacuum system.

So far, beside four-stage versions, three-stage vacuum pump sets have been used as mechanical vacuum pump sets combining the first and second vacuum stage with classical fine-vacuum rotary-piston pumps, with a screw vacuum pump as pre-stage pump in the third stage to the atmosphere.
As the available machine stages allow three-stage pump sets only to be designed with low-capacity modules from ≤10,000 up to a maximum of 40,000 m^3/h, each steel degassing station required a great number of modules and, hence, a correspondingly great number of individual machine units – for example, up to 180 single machines for RH plants.

Design and operation of three-stage mechanical vacuum pump sets

Use of fine-vacuum HV machine stages for RH/VOD operation in three-stage pump sets.

For a stable suction capacity in both the rough and fine vacuum, it is indispensible to provide for sufficient pre- gas and interstage cooling of the process gas. In the past, pre-gas and interstage cooling was often not provided or was insufficient for three-stage pump sets,leading to instability in the final vacuum in fine-vacuum operation of ≤10 mbara.

As a result of a higher suction temperature (without gas cooling) of the second HV stage inlet, the pressure ratio between the first and the second HV stage is increased and the suction capacity of the first HV stage reduced. In rough-vacuum operation between 1,000 and ≥100 mbara, the absence of appropriate pre- gas cooling causes damage to the equipment.

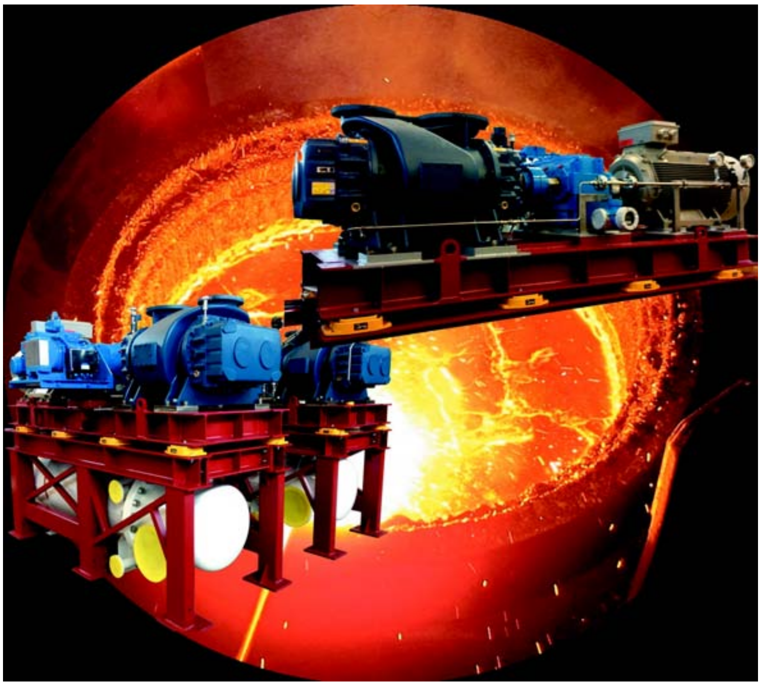

Fig. 1
Pump sets in stalled at voestalpine foundry in Linz

The mechanical clearances of fine-vacuum HV machines are designed for vacuum operation in the range from ≤10 mbara to approx. 10^{-3} mbara.
For higher operating pressures, they are not generally suitable.

Fine vacuum HV- machines must be protected by a maximum permissible Δp and maximum permissible power rating, pump-down from a rough vacuum of <200 mbara down to a fine vacuum of ≤10 mbara is only possible for a short period of approx. ≤6 min. Permanent rough-vacuum operation of HV machines is not permitted!

In the fine vacuum of ≤10 mbara, higher outlet temperatures of the HV machine are without effect within a certain range. This is because the mass flow in the machine is very low compared to the rough vacuum. With an equivalent pressure ratio, in the fine vacuum the outlet temperature is therefore lower than in the rough vacuum.

However, this may lead to misinterpretations of the outlet temperature and the thermal operating reliability of the HV stages. If these low outlet temperatures found in the fine vacuum range are taken as the basis for the assessment of the outlet temperature of HV stages in the case of RH/VOD pressures in the <400 to >50 mbara range, the result will be damage to the machines - eventually severe damage.

Use of fine-vacuum HV machine stages for pressure and mass flow control in RH/VOD operation.

For this application, the employed HV stages and components must be ATEX-compliant and pressure-shock resistant.

In RH/VOD operation in the <400 to >50 mbara range, the possibilities of pressure and mass flow control via HV stages in a three-stage pump set configuration are limited.

Reducing the rotary speed of the HV machine will deteriorate the volumetric efficiency and increase the outlet temperature. Due to the low permissible power rating of HV driving motor, the maximum permissible Δp of the machine stage and the rotating masses of the rotor, gear and engine, the rotary speed of the HV stages may only be changed very slowly using a frequency converter. The pressure control via the HV stages is limited by the lowest critical rotary speed and the point at which blower splash lubrication starts to fail.

Process-related vacuum pressure variations in RH/VOD plants falling below the design/ set point pressures or below the design/ set point speed can be corrected only very slowly by means of HV stages, and variations exceeding the design limits cannot be corrected at all.

Therefore, in an RH/VOD system safe and effective pressure control is only possible via the third stage – the screw vacuum pump.

	SGI pump set Five (four)-stage	**Pump set "A"** **Three-stage**	**Pump set "B"** **Three-stage**
	Pump-down / **Regular RH- operation**		
Process pressure mbara	**Two-stage** Pre-inlet machines/ screw pumps kW	**Single-stage** 16 high-capacity screw pumps kW	**Single-stage** 80 low-capacity single-screw pumps or 40+40 twin-screws arranged on top of each other kW
500	777 (1017)	870	1320
200	804 (882)	770	1280
100	694 (555)	720	1080
50	406 (385)	640	800
10	167 (247)	610	640
Mean	**570 (617)**	**722**	**1024**
	Final vacuum operation		
Process pressure mbara	**5-stage** 22 (19) high-capacity individual machines kW	**3-stage** 45 high-capacity individual machines kW	**3-stage** 180 low-capacity individual machines kW
4	1000 (939)	1320	1380
2	609 (624)	1320	1070
1	407 (471)	930	940
0.67	336 (415)	885	820
Mean	**588 (612)**	**1050**	**1052**

Fig. 2
Comparison of two different three-stage pump sets with the SGI five-stage pump set

However, without an RH or VOD- bypass, hot gas (without pre- cooling) will flow through the standing or uncontrolled driven rotating pistons of the first and second HV stage. The uncontrolled rotation speed in the rough vacuum of >50 mbara has negative effects on the machine shaft seals and bearings. In a situation of prolonged operation with through-flowing hot gas, both the HV machine casing and the gear lubricant may become excessively hot.

RH- or VOD pressure control exclusively by screw vacuum pumps naturally requires a higher number of screw vacuum pumps than would be necessary for final vacuum operation at ≤10 mbara.

Use of a great number low-capacity HV- stages in a three-stage pump set configuration.

Manufacturers of vacuum equipment have been increasingly offering low-capacity machines on the market. These low-suction HV machines with canned drive and designed for clean-room operation are now used in steel degassing lines, e.g. in 150-t RH plants with up to 180 individual machines.

However, operating such a great number of small capacity canned drive pumps, each designed for a suction rate of approx. 10,000 m^3/h, as first and second HV stages bears a high risk of errors and failure.

In order to achieve the required suction capacity in final vacuum operation, the individual canned drive pumps must constantly be operated at 70 Hz.

Control of such a great number of stages of canned drive machines is highly complex but nevertheless absolutely necessary, among others due to the permissible maximum Δp of only 30 mbar at 60 Hz and only 14 mbar at the final rotary speed of 70 Hz.

In addition to the rotary speed and interstage pressure control, it is also necessary to monitor vibrations and the temperature of the housings.

System- inherent pressure variations, such as a sudden vacuum collapse due to leakages/ingress of external gas or abrupt flooding or purging as well as entrained contaminations, interfere with the pumping stages, resulting in increased vibrations and excessive bending of the rotary pistons and eventually leading to damage of the bearings.

If Δp is greater than permitted, the machine heats up more than usual. This leads to an expansion of the rotary pistons towards the side plates and inevitably to non-repairable damage of the machine.

Moreover, small HV pumping stages with permissible Δp between approx. 30 and 14 mbar, may only be switched into the extraction process at approx. 10 mbara to achieve a final vacuum of 0.67 mbara.

In RH plants, typical cycle times are ≤4 min, in VD/VOD plants 5 to 6 min. In order to be able to achieve these times in three-stage vacuum pump sets made up of low-capacity blowers and/or small permissible Δp per stage, it is necessary to have a large number of vacuum screw pumps operate in parallel before the HV pumps can be switched in at <10 mbar to support the evacuation.

Advantages of four- or five-stage pump sets

As described above, numerous installations of three-stage vacuum pump sets suffered mechanical damage due to excessive thermal and mechanical loading of the machine stages.

Therefore, throughout the world, three-stage mechanical pump sets consisting of a great number of individual units are being converted to more reliable and energy-efficient four- or five-stage pump sets featuring rotary piston machines from a German manufacturer, which are designed for large stages ranging between 40,000 and 90,000 m^3/h and equipped with appropriate cooling and control systems.

The greater the number of screw vacuum pumps, the higher the energy consumption of the pump sets. In contrast to this, in case of volumetric rotary piston machines, the smaller the Δp and the process pressure, the lower the energy consumption. Screw vacuum pumps are characterized by internal compression which does not decrease significantly with a decreasing pressure, unless in the 1,000 to ≤100 mbara range.

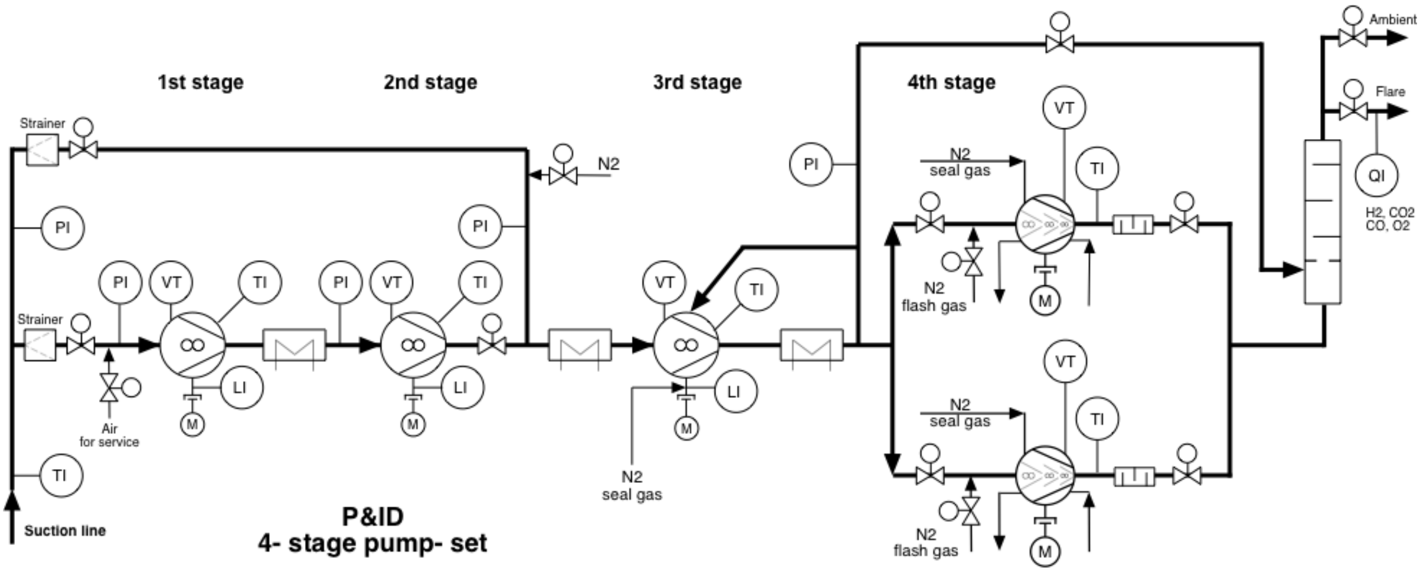

Fig. 3
P & I diagram of the pump set installed at voestalpine in Linz

Against this background, energy savings in pump sets are only feasible by increasing the number of stages of the rotary piston machines while using as few as possible energy-intensive screw vacuum pumps and limiting their use to ≤60 mbara and to the final vacuum range of ≤10 mbara.

This can only be achieved by four- or five-stage vacuum pump sets in combination with a pre-inlet machine/screw vacuum pump to the atmosphere.
The HV machine stages used in four- or five-stage vacuum pump stages are designed for a permissible Δp of 200 mbar of the HV stage and, with the use of the pre-inlet machines, for a Δp of 800 mbar at moderately low speeds. This guarantees that these machine stages can withstand higher mechanical loading during the robust operations of RH/VOD steel degassing.

Thanks to the greater permissible Δp of the HV machines employed in the first and second HV stage, shorter evacuation times are achievable because these machine can start supporting the evacuation processes at a higher pressure.

To prevent machine damage, the design of the SGI pump sets generally includes pre- and interstage cooling, machine temperature, stage vibration and stage pressure monitoring as well as tightness of the drive shaft sealing.

In situations in which only cooling water of approx. 35 to 40° C is available, four- and five-stage vacuum pump stages are superior to three-stage configurations due to the correspondingly smaller Δp of the individual stages and the consequently lower thermal loads acting on the individual stages.
Screens with Δp sensors and designed for minimum pressure loss are arranged in the central inlet piping of the pump set. Any blocking of screen due to dust will be signalled by the Δp alarm, avoiding dust propagation inside the pump set.

Comparison of energy consumption by way of the example of a 150 t RH- line

Figure 2 compares two designs "A" and "B" of a three-stage pump set with a five (four)-stage pump set.

- Operating mode: Evacuation/regular RH operation:
- Assumptions: Effective suction capacity of approx. 40,000 m^3/h during pump-down/regular RH operation with pre-inlet machines to the atmosphere from approx. 1,000 to approx. 10 mbara.
  Air suction capacity, entry temperatures for the five (four)-stage SGI vacuum pump set of up to 130° C possible thanks to pre-inlet cooling.

Fig. 4
Single stages of the pump set at the voestalpine foundry:
a) 1st and 2nd stage HV vacuum pump stage,
b) 3rd stage, pre-inlet vacuum pump stage,
c) pre-inlet and interstage cooling,
d) 4. vacuum pump stage: screw vacuum pumps

- Based on the data in figure 2, the following results: Energy consumption of three-stage pump set “A” versus five-stage:
  722 — 570 = + 152 kW for the respective operating data.
  Energy consumption of three-stage pump set “B” versus five-stage:
  1,024 — 570 = + 454 kW for the respective operating data.
- Operating mode: Final vacuum ≤4 to 0.67 mbara:
- Assumptions: Effective suction capacity of 600,000 m^3/h at a final vacuum of approx. 4 to approx. 0.67 mbara. Air suction capacity, entry temperatures for the five (four)-stage vacuum pump set; calculation basis max. 80° C.
- Based on the data in figure 2, the following results: Energy consumption of three-stage pump set “A” versus five-stage:
  1,050 — 588 = + 462 kW for the respective operating data.

  Energy consumption of three-stage pump set “B” versus five-stage: + 464 kW.

This shows that due to the high energy input a three-stage vacuum pump set – be it in a configuration with just a few high-capacity machines as in “A” or with a great number of low-capacity machines as in “B” – will not reach the efficiency level of a five (four)-stage pump set. This does no even take into account the high maintenance and service costs associated with the operation of a great number of small pumping stages. The investment costs of a five-stage vacuum pump set are almost identical with those of a four-stage system.
For plants of this size, SGI prefers a five-stage configuration because this provides a more favourable thermal behaviour, lower mechanical stress acting on the stages thanks to the lower Δp per stage and enables the use of cooling water of up to approx. 40° C.

Explosion protection requirements for mechanical pumps in steel degassing operations

In a VOD installation, the liquid steel may temporarily generate and release an explosive gas mixture in the pump-down phase and in the VOD mode. This makes it necessary to consider the following aspects.

Description and operation of an Ex-proof pump set

Figure **3** shows the P&I diagram of the pump set in a 50-t vacuum decarburization plant (VOD-VD), which since June 2013 has been in operation with a combination of rotary piston blower and screw compressor, making it one of the first VOD systems worldwide to use this type of pump set configuration.

The vacuum pump set consists of two parallel pump sets, each with four stages arranged in series.

- Pump-down and VOD mode, figures **4b** and **4d**:
  3rd/4th stage: Up to a defined intermediate pressure, pump-down directly to the atmosphere bypassing the fourth stage. In the VOD mode, holding of VOD pressure.
  From a defined suction pressure, both stages operate in series to the atmosphere.
  1st/2nd stage: Not in operation and shut off by valves.
- VD mode, figures 4a-d:
  1st/2nd stage: Activated upon reaching a defined pressure, flap valves open.
  Pump-down with all four stages in series down to the final VD pressure of 0.67 mbara.

Operator's Responsibility

The criteria for the assessment of the risk of explosion and the definition of explosion prevention and protection measures have been stipulated in the European Directives 1994/9/EU (ATEX 100 a) and1999/92/ EU (ATEX 118 a) uniformly for all memberstates of the European Union. These criteria are legally binding. Corresponding regulations in place in other countries must be examined with a view to their applicability.
The plant operator is responsible for taking the necessary care for ensuring that the period during which such an explosive gas mixture may occur and the risk of explosion are kept at an acceptable low level.
In order to minimize the probability of incidents, the following three strategies shall be applied:

- Avoid/reduce explosiveness
- Avoid/encapsulate (isolate or disable) potential ignition sources
- Limit/minimize the effects of a potential explosion.

Explosion protection and prevention concept

Explosion protection and prevention are among the most safety-critical tasks of a plant operator.
An Ex- protection and prevention concept must include both technical and organizational measures for risk minimization. The safety manual must be kept up to date and the personnel on site must be familiar with it.

A consistent concept will include technical and organizational measures aimed at minimizing risks. Such an Ex- protection and prevention concept will be agreed between the responsible supervisory authority, the plant operator and the plant builder, specifying the requirements for an operating approval.

In VOD plants, the potential risk of explosion comes from the presence of CO and the varying concentration of CO depending on the excess oxygen in the process gas. As a requirement for the VOD process, oxygen is injected into the melt. In case of fault, this oxygen will not be completely used up and may account for up to 30 % of the extracted gas mixture.

The designation of Ex- zone(s) and Ex- protection measures is based on safety-relevant parameters.
These parameters refer to the CO/air mixture under atmospheric conditions. Under vacuum conditions, the maximum explosion pressure is lower in proportion to the process pressure of the gas mixture.
Additionally, it must be taken into account that the lower Ex limit and the critical oxygen concentration are lower at higher temperatures, figure **5**.

Fig. 5 Safety-relevant data					
Explosion pressure	ED_{CO}	7.3	ED_{H2}	7.4	barg
Lower Ex limit	UEG_{CO}	10.9	UEG_{H2}	4	% vol.
Critical oxygen consentration	SK_{CO}	4.3	SGK_{H2}	5	% vol .

For the designation of Ex- zones in pumping operations involving potentially explosive gas mixtures, the pump-down phase and the VOD mode must be considered separately.
The process involves approx. 6 min of pump-down versus approx. 60 min of VOD operation. This means that in the VOD mode an explosive gas mixture is likely to occur and not during very short periods. Therefore the plant will have to be designated as zone 1, figure **7**.

Fig. 6 Examples of process gas mixture (in vol. %)

Pump-down mode		**VOD mode**		**VD mode**	
CO	5-10 %	CO	30-80 %	CO	<3 %
H_2	<1	H_2	<1	H_2	3
N_2	70	N_2	<20	N_2	<50
Ar	15	CO_2	10-30	Ar	<40
O_2	20	Ar	<5		<4
		O_2	<5		

Fig. 7	**Definition of the Ex zones:**
Zone 0	continuously present or present for long periods
Zone 1	for short periods
Zone 2	not likely to occur and only for a very short time

Taking into account that in the VOD mode the inflow of O2 is characterized by finite inertia and usually several batches are degassed per working shift, it is realistic to assign the waste gas flow to Ex zone 1.

In the VD mode, the waste gas mixture is not explosive / too lean due to the low content of combustible components and the relatively high content of inert substances, figure **6**.

In the VOD mode, the VD pumps of the first and second stage are not needed, i.e. not switched on.
Under process-technological and safety-relevant considerations it therefore makes sense to switch the VD pumps (stages 1 and 2) off-line in the VOD mode and separate them from the waste gas flow as an explosion protection measure, figure **3**.
Therefore, during the pump-down and in the VOD mode the pumps will be isolated from the suction line and the stages 3 and 4 by means of suitable flap valves taking into due consideration the maximum explosion pressure.

Protection of vacuum pump stages against higher oxygen concentration

During VOD treatment, oxygen is injected into the melt for oxidation. In case of poor reactivity, there is an elevated concentration of O_2 in the waste gas evacuated by the vacuum pumps.
This gas may enter the lubrication chambers in the blowers and the screw pumps. Due to the high O_2 concentration of the gas, there is the risk of reactions.
In order to prevent this from happening, inertization of the pump set will start when a max. O_2 of 30 % exists for max. 10 min.
As additional measures oils suitable for use in O_2-containing atmospheres are used and the lubrication chambers are purged by N_2.

Pressure-shock resistant design of the pump sets

Due to the process requirements, the third and fourth stage compresses explosive gas from the vacuum to the atmosphere.
Consequently, the partial pressure of the explosive gas mixture to be pumped and the potential explosive pressure are relatively high.

Therefore the components must be protected by a housing that would not burst in the event of an explosion. The machines of the third and fourth stage are constructed with a “pressure-shock resistant housing”, capable of withstanding the maximum explosion pressure.

Therefore it is reasonable and required by the Ex study to comply with the requirement that at least all those components through which process gas flows during VOD operation shall be pressure-shock proof.

The blowers of the first and second stand do not receive a pressure-shock-proof design, but they are separated from the rest of the plant by pressure-proof valves.

Ventilation of the machine room

Due to the potential risk of CO leakage, it is recommended to operate the VOD stages in a ventilated machine room, in which the CO concentration of the ambient air can be sufficiently reliably monitored and limited.
Care must be taken that the maximum permissible ambient air temperature is not exceeded in order to ensure that the electrical components can operate within the temperature ranges for which they have been designed.

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